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FINAL REPORT ON DEVELOPMENT AND IMPLEMENTATION OF SHUTTLE/IUS PROXIMITY OPERATIONS FLIGHT DESIGN SOFTWARE

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Prepared by S. W. Wilson
S. W. Wilson, Manager
Shuttle/IUS Proximity Operations
Software Project

Approved by D K Phillips
D. K. Phillips, Manager
Systems Engineering and
Analysis Department

Systems Engineering and Analysis Department

TRW
DEFENSE AND SPACE SYSTEMS GROUP
Houston, Texas

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ABBREVIATIONS

DAP	digital autopilot
FDS	Flight Design System
HFRMP	High Fidelity Relative Motion Program
IUS	Interim Upper Stage
JSC	Johnson Space Center
MPAD	Mission Planning and Analysis Division
OMS	orbital maneuvering system
PIDI	Particle Impact Damage Integrator
RCS	reaction control system
SHAP	Supersonic-Hypersonic Arbitrary-Body Program
SRM	solid rocket motor
SSFS	Space Shuttle Functional Simulator
SSUS	Spinning Solid Upper Stage
STS	Space Transportation System
TDRS	Tracking and Data Relay Satellite

1. INTRODUCTION

The purpose of this report is to summarize the activities that were carried out in accordance with the Work Statement for Schedule II of Contract NAS9-14723, as modified by Amendment CCA 1. This report is the final deliverable item required by the aforesaid contract.

Detailed descriptions of the results of Schedule II activities are contained in References 1 through 25. These references are represented by the various symbols appearing in Figure 1, which is a graphical history of contract activities and the expenditure of engineering manhours under Schedule II. A similar representation of Schedule I activities in contained in Reference 26.

The primary objective of the Schedule II work statement was to provide the JSC Mission Planning and Analysis Division (MPAD) with software which could be used for simulating, visualizing, and analyzing the complex relative motions of the Space Shuttle Orbiter and a free-flying upper-stage/payload configuration. On-orbit flight activities involving the Orbiter and a nearby free-flyer are referred to, in a generic sense, as "proximity operations". Because its main purpose is to facilitate the design of maneuver sequences associated with such activities, the software developed under the Schedule II work statement is characterized as "proximity operations flight design software".

The development of effective flight design requires an intimate understanding of the flight designer's problem. In the case at hand, the designer's problem involved facets of orbital operations that had not been previously explored well enough for the software requirements (much less the best way to satisfy them) to be fully understood. In order to gain the necessary understanding, the software developers participated in actual flight design exercises, supporting MPAD in the formulation of Conceptual Flight Profiles for deployment of the TDRS-A and Galileo spacecraft. The overall development process was an iterative one wherein software was built to meet identified requirements, applied to real problems, and then modified to meet the new requirements that became evident.

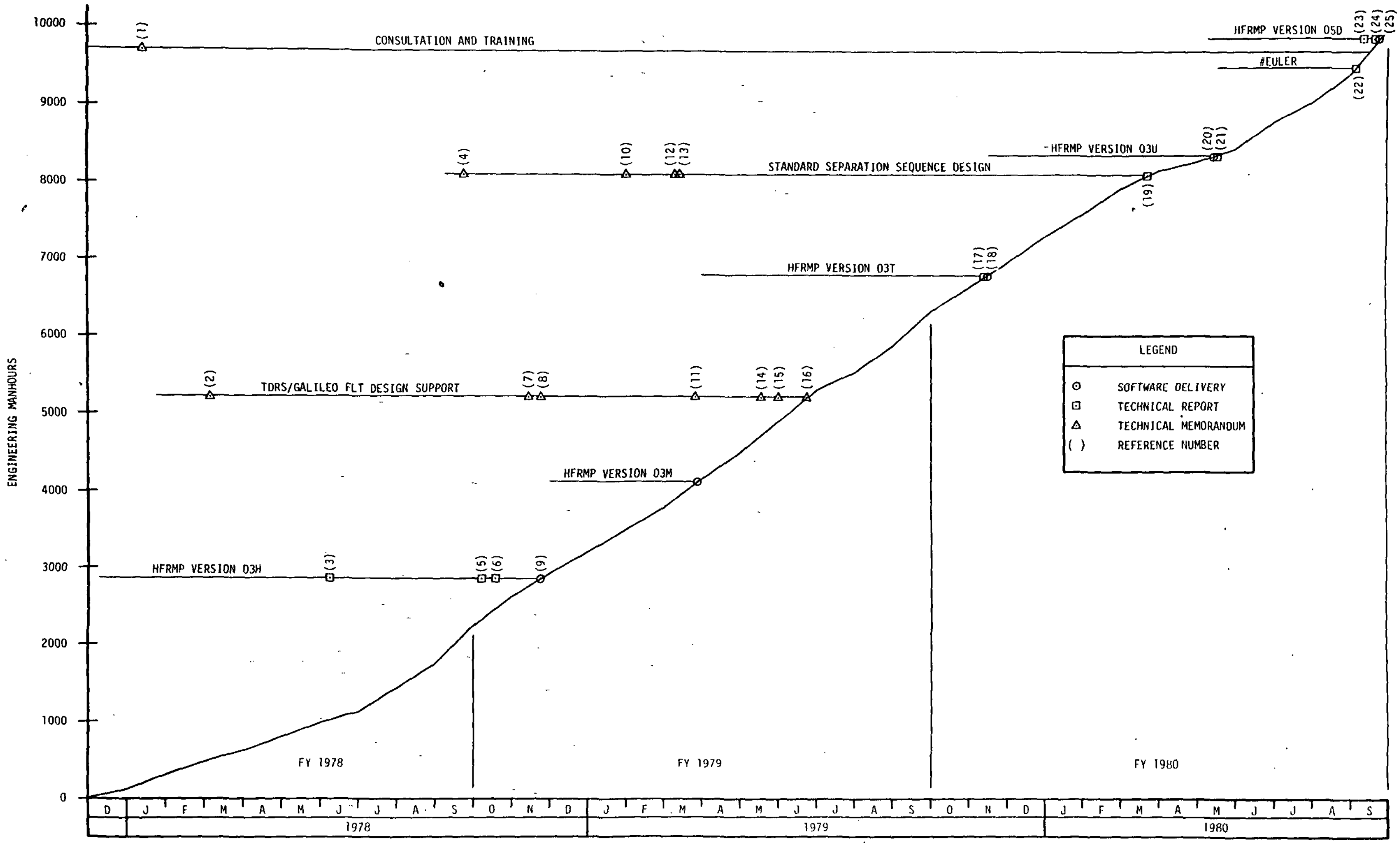

Figure 1. History of Schedule II Contract Activities

FOLDOUT FRAME

FOLDOUT FRAME

2. MAJOR ACTIVITIES

2.1. DEVELOPMENT AND IMPLEMENTATION OF THE HFRMP

The High Fidelity Relative Motion Program (HFRMP) is a 12-degrees-of-freedom trajectory/attitude numerical integration program (six degrees of freedom for each of two vehicles) which was developed and implemented on the MPAD HP-9825A desk-top computer systems. Included in the HFRMP are a solar and a lunar ephemeris and models of the oblate earth, a rotating atmosphere, the Orbiter's OMS/RCS/DAP sytems, Orbiter vents, rotor dynamics, and upper stage propulsion systems. Although designed primarily for the analysis of proximity operations, it has proved to be useful in other areas such as attitude /stability analysis, propulsive consumables estimation, and trajectory perturbation studies.

An unique identification was assigned to each of the various configurations of the HFRMP that were developed to test new techniques and algorithms. Only five of these - HFRMP Versions 03H, 03M, 03T, 03U, and 05D - were ever released for general production use (i.e., for use by personnel other than the software developers, themselves). Before release, every production version was tested extensively to verify the new code. Where possible, HFRMP results were compared against data generated by well-tested and reliable software such as the MPAD Reference Mission Design Analysis Program (RMDAP) and the Space Shuttle Functional Simulator (SSFS). In cases where no data of the needed type were available from reliable sources, verification was based on independent computations made with hand-held calculators, or in some cases by defining HFRMP inputs in such a manner that the proper output could be accurately predicted by the application of basic principles.

2.1.1. Version 03H

The first production version of the HFRMP, 03H, was released in November 1978. Its basic capabilities are described in Reference 5, which contains a detailed description of its OMS/RCS/DAP models, and comparisons of Orbiter propellant consumption data generated by the HFRMP and the SSFS. In addition to its basic capability for generating digital and graphical data to describe the relative motions of the Orbiter and a deployed upper-stage/payload combination (which, for the sake of brevity, will sometimes be referred to herein

as simply "the Payload"), Version 03H and all subsequent versions had the capability to compute data relating to potential damage of Orbiter windows and thermal protection tiles by solid particles in the exhaust of upper-stage solid rocket motors (SRM's). This latter capability resides in a special HFRMP trajectory postprocessor called the Particle Impact Damage Integrator (PIDI). The basic equations of the PIDI are described in Reference 3. The User's Guide for Version 03H is contained in Reference 6, which applies also (with minor variations) to Versions 03M, 03T, and 03U.

2.1.2. Version 03M

Version 03M, which was released in April of 1979, was a relatively minor revision of 03H. Some coding errors were corrected, the Orbiter's RCS force and moment tables were updated to conform to recently acquired data, some additional flight control options were implemented, and interim thrust tables were added to allow the simulation of SSUS-A and SSUS-D SRM burns. (Version 03H had contained only one SRM thrust table, for the IUS.)

2.1.3. Version 03T

Aside from a general re-arrangement of the code to make it more efficient and easier to explain in Reference 17, the major difference between Versions 03M and 03T was the inclusion (on the program disk for the latter) of pre-defined flight control specifications for 24 standard Orbiter/upper-stage separation sequences. These standard sequences, which apply to the deployment of IUS, SSUS-A, and SSUS-D stages, are defined in HFRMP input data files of a particular type referred to as Flight Profiles. The design of these standard sequences is discussed in Section 2.2.2.

2.1.4. Version 03U

Version 03U, which was released in May of 1980, differed only slightly from Version 03T. Some slight changes were made in the definition of input parameters, and some minor coding errors were corrected.

2.1.5. Version 05D

Although it retained the basic dynamical models used in earlier versions

of the HFRMP, Version 05D represented a major revision in terms of flexibility and ease of use. Its release necessitated a complete re-write of the User's Guide (Reference 24). Several new processors were added to allow user access to data tables that were, in effect, "hard-wired" in earlier versions of the program. The Flight Profile Editor was re-worked in such a fashion as to remove most of the drudgery that had previously accompanied the definition of a complicated Flight Profile, and a new processor was added to facilitate the management of the user's personal data files.

In addition to changes oriented toward increasing program flexibility and user convenience, Version 05D incorporated a new RCS/DAP limit cycle model (Reference 23) to provide more accurate computations of RCS propellant consumption and uncoupled thrust acceleration. Analytic solar and lunar ephemeris models were also added to support the computation of data relating to solar illumination of the Orbiter and the Payload, and possible interference with visual and star-tracker observation of the Payload from the Orbiter. Reference 25 contains a list of specific changes incorporated into Version 05D.

2.2 DEVELOPMENT OF ORBITER/UPPER-STAGE SEPARATION TECHNIQUES

One of the major problems associated with STS flight operations, and the one which was the primary impetus for development of the HFRMP, has to do with the design of maneuver sequences to separate the Orbiter from a just-deployed upper stage. The SRM's used as major propulsion units for the standard upper-stage types (IUS, SSUS-A, and SSUS-D) expel solid particles that are capable of inflicting intolerable damage on the Orbiter. The Orbiter's thrusters, on the other hand, can destabilize the upper stage or ruinously contaminate the surface of the satellite it is transporting, if they are fired indiscriminately in the near vicinity of the Payload. The requirement for limiting the detrimental effects of the two vehicles on one another, combined with a number of additional constraints and requirements that have to be satisfied, makes for a very difficult flight design task (Reference 19).

In the interest of minimizing the recurring costs of flight design and training, it has long been the goal of the MPAD to standardize the Orbiter/upper-stage separation sequence. That is to say, the goal has been to define a more-or-less fixed sequence of maneuvers that could be used for the deployment

of any standard upper-stage type, with only minimal flight-to-flight variation. Early attempts in this direction were foiled by the complexity and pervasiveness of the interactions between the flight design requirements. It quickly became evident that the only hope of success lay in building a special flight design tool (the HFRMP) and applying it in integrated multi-discipline exercises aimed at designing complete flight profiles to satisfy the requirements of specific upper-stage/satellite combinations. Only in this fashion would it be possible to understand the interaction of flight design requirements well enough to standardize the separation sequence.

2.2.1. Flight Design Support for the TDRS-A and Galileo Deployment Flights

Although consultation services (Section 2.4) were provided for other exercises, direct support of MPAD flight design efforts was limited to the TDRS-A and the Galileo deployment flights. The TDRS-A flight, being the more imminent, received by far the greater amount of attention.

In addition to the generation of data for MPAD flight design documents (References 27-29), flight design support involved attendance at a number of technical meetings, and the preparation of oral presentations for some of them. With regard to the TDRS-A separation sequence, one of the major concerns expressed by meeting attendees was that the scheduled firings of the Orbiter thrusters would excessively contaminate sensitive surfaces of the TDRS-A. (The expansion angles of the thruster plumes are so great that complete avoidance of impingement on a deployed Payload is virtually impossible.) However, in this regard, the efficacy of the recommended separation sequence was vindicated by an independent analysis (Reference 30), which showed that Orbiter thruster firings during the separation sequence would contribute much less than one percent of the total contamination expected to accumulate during the deployment flight.

2.2.2. Design of Standard Maneuver Sequences

The complexities of the Orbiter/upper-stage separation problem are such that the goal of defining one standard maneuver sequence appears to be unachievable. On the basis of insights gained from the specific design exercises referred to in Section 2.2.1., the best that has been done so far is to define - for each stage type - a set of eight (8) standard sequences, one of which

should at least come very close to satisfying the requirements of any particular flight. (On the basis of anticipated similarities in flight requirements, it is expected that two or three of the standard sequences will suffice for the majority of deployments of a given stage type.)

Reference 19 contains detailed descriptions of standard separation sequences applicable to the deployment of IUS, SSUS-A, and SSUS-D stages, along with a discussion of the basic design rationale. The flight control specifications for these standard sequences are contained in Flight Profile definitions which reside on the HFRMP program disk, whence the appropriate one can be recalled by the flight designer as a baseline solution for the specific problem he faces. The current definitions represent a "first cut" at the problem of defining a comprehensive set of standard sequences, and are subject to modifications that are almost certain to be found necessary by integrated flight design exercises in the future.

2.3. DEVELOPMENT AND IMPLEMENTATION OF THE EULER ANGLE CONVERSION PROGRAM (#EULER)

Near the end of the contract period it became evident that the utility of the HFRMP would be enhanced significantly if provisions were made for a more general capability to transform its input data, which comes from many different sources in many different formats. Such a general accommodation of data format variations was not provided for in the original Work Statement for Schedule II, and therefore, a revision was issued as Amendment CCA 1.

The basic requirements of Amendment CCA 1 were two-fold: (1) to provide additional options for transformation of the translational states of the Orbiter and the Payload, and (2) to provide the capability to convert the attitude definition for either vehicle from any sequence of Euler angle rotations to any other Euler sequence, of which there are 12 possibilities. The first of these requirements was satisfied by modifications of the HFRMP code itself, which were incorporated in Version 05D. The second was satisfied by the construction of a special Euler Angle Conversion Program (#EULER) which is described in Reference 22, and which resides on the HFRMP Version 05D program disk as a stand-alone program.

2.4. CONSULTATION AND TRAINING SUPPORT TO THE MISSION PLANNING AND ANALYSIS DIVISION

Throughout the contract period, consultation and training support was provided to MPAD personnel in the areas of (1) special flight design techniques associated with STS proximity operations, (2) utilization of the HFRMP and the HP-9825A Desk Top Flight Simulator (which was developed under the Schedule I Work Statement), and (3) implementation of HFRMP capabilities in the MPAD Flight Design System (FDS). Support of the FDS implementation task (which is being performed by another contractor) involved the drafting of preliminary implementation requirements (Reference 1), the review of implementation documents, and supplying data for testing and de-bugging the FDS code.

3. RECOMMENDATIONS

The basic aerodynamic model of the Orbiter is represented in the HFRMP by curve fits of the data contained in Reference 31, which were generated by the Supersonic-Hypersonic Arbitrary-Body Program (SHAP). The cited SHAP data apply to the (cargo bay) doors-closed configuration of the Orbiter, whereas the doors will be open during most on-orbit operations. Accordingly, on the basis of a rather crude analysis, the HFRMP curve fit coefficients were adjusted in an attempt to compensate for the effect of open doors.

A partial set of SHAP data for the doors-open configuration has since become available, and it indicates that the analytical adjustment of the curve fit coefficients was not very accurate. Because a re-generation of the aerodynamic curve fits will require a considerable investment of time, and because the current model of atmospheric density in the HFRMP is also rather crude, it was not deemed profitable to re-work the curve-fit model until the complete set of doors-open SHAP data becomes available. When these data do become available (which was not the case at the end of the contract period), a re-generation of the curve fit coefficients is recommended. At the same time, consideration should be given to the implementation of a more sophisticated model of the atmosphere, such as E. C. Lineberry's simplified version of the Jacchia model.

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